Integrated Water Quality Trend Analysis

Stewart, R. E. and Smith, D. H., Ph.D.   Virginia Department of Environmental Quality, Richmond, Virginia, USA

1. INTRODUCTION

With each cycle of the 305(b) Integrated Report more stream segments and estuarine / reservoirs polygons are added to the 303(d) list of impaired waters. At the same time many resources have been invested towards restoration of water quality. Are our restoration efforts in vain? Why is there a dichotomy between more impaired water listings and more efforts to restore our Nation's water quality? What is needed is a better indicator of our progress, an indicator based on numeric water quality data.

The integrated water quality (IWQ) trend analysis is a new statistical procedure developed to detect trends by maximizing the amount of data used. The IWQ is a seasonally derived nonparametric scoring procedure that is applied to various waterbody types at the watershed scale. The impetus for the creation of the IWQ was to detect and explain changes in water quality over time more descriptively than the traditional 305(b) integrated report. The IWQ was developed by D.H. Smith and R.E. Stewart at the Virginia Department of Environmental Quality with the encouragement and support of L. Merrill, U.S. Environmental Protection Agency, Region 3.

Traditional trend analyses on water quality variables are limited to fixed long term monitoring stations. The modified seasonal Kendall procedure is a common nonparametric method which is robust against outliers, censored values, and unevenly spaced gaps in time and seasonal frequency[1,2,3].

The implementation of restoration projects of impaired stream segments involves a watershed approach of identifying sources and loadings. Generally the targeted fixed trend stations are not of sufficient density to determine the effectiveness of restoration efforts. In order to determine water quality trends in an entire watershed other sources of data can be helpful. A recent long term trend analysis of the Commonwealth of Virginia's waters using the modified seasonal Kendall statistic included 436 fixed trend stations. When applying the IWQ over the same twenty year time period we were able to incorporate 5,776 stations into the analysis.

Based on our previous work using the formal Kendall analysis when compared to the results of the new IWQ trend analysis, we were able to statistically reveal vast improvements in water quality across the Commonwealth[4].

2. METHODOLOGY

The IWQ uses a reference time period to derive the upper quartile, lower quartile and the interquartile range which are used as reference concentrations. Raw water quality concentrations are then compared to the reference concentrations and scored accordingly. The reference period selected was for the most recent ten year block of data, 2001 to 2010. These data represent the best quality controlled data and were collected using the most sensitive instrumentation. The quartiles and inter quartile range are calculated from the reference period for each water quality variable by month, by water body type (stream/river, estuary, reservoir), and by watershed (HUC 5th order 10 digit watersheds). This type of stratification by season, water body type and watershed is referred to as "by group processing". This by group processing is important in that variations in season and waterbody type within a watershed are locally confined and used to generate very specific reference conditions.

Once the reference concentrations are calculated each individual water quality measurement for all stations for the entire period of 1991 to 2010 is compared to the reference numbers again by month, by water body type, and by watershed. When a data point is in the lower quartile meaning lower concentration, high quality, a score of 100 is given. The interquartile range receives a score of 50 and the upper quartile, higher concentration lower water quality, is set to zero. Next the average score by year by waterbody type and by watershed is calculated. Scores are plotted by year and the long term trend in water quality is calculated via linear regression (score vs. year) including the confidence interval (p). An example of the graphical output for one watershed, variable, and water body is seen in Figure 1 Fecal Coliform Lower James River. In this particular example the bacteria score is generally increasing from year to year or in other words the higher the score the higher the water quality, lower bacteria concentration. From Figure 1 we see that the water is getting cleaner as the years pass. The IWQ uses this convention throughout, that being a positive slope indicates improving water quality.

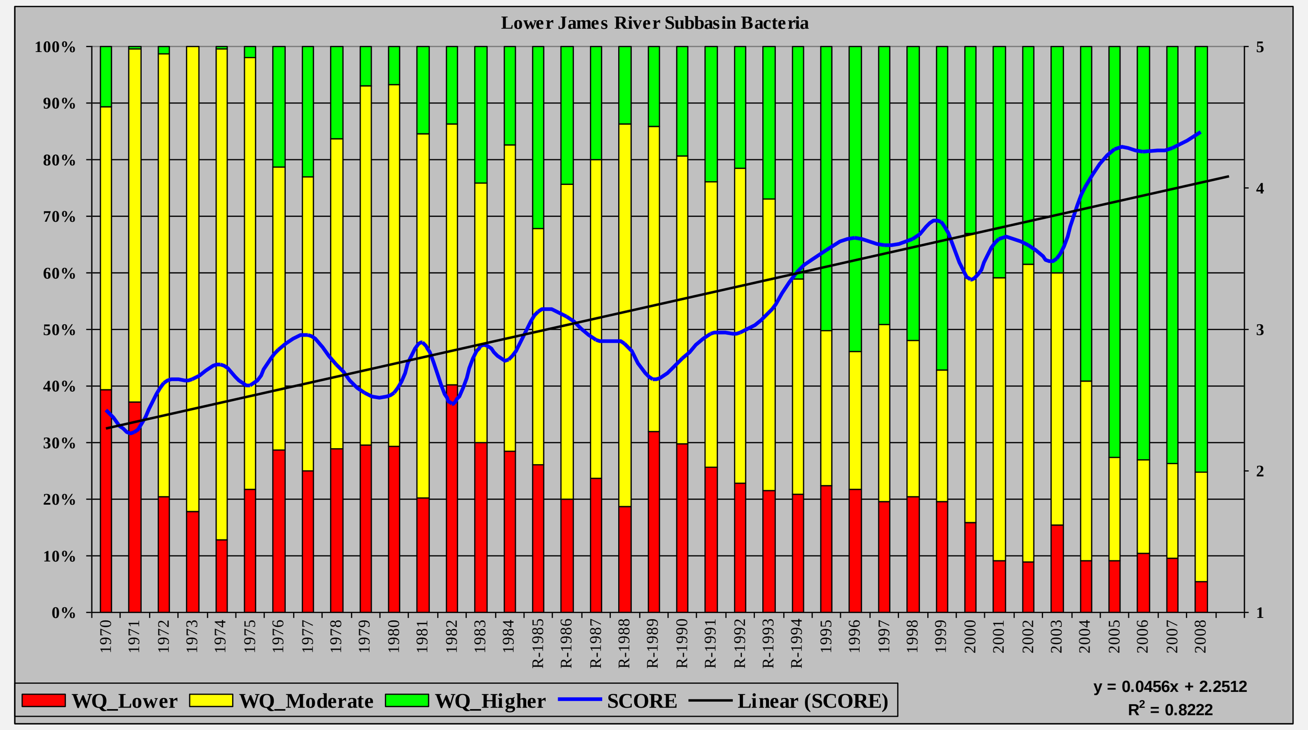

Figure 1 Fecal Coliform Lower James River

2. METHODOLOGY, continued

The IWQ methodology is very robust against censored data, those being reported as less than the detection limit or those above a certain upper value as with the case of bacteria colonies that are too numerous to count. Inspection of the raw data for those variables with remark coded values below the detection limit regardless of changes in detection limit over time indicate almost every censored value will fall in the lower quartile. Upper detection limit data remark coded data occur infrequently and only for bacteria measurements and enjoys the same robustness of occurring in the upper quartile regardless of censoring point.

We define those statistically significant improving water quality trends by those regressions with a 90% confidence value and a slope greater than 0.0 and are identified in this report as having "SIGNIFICANT IMPROVEMENTS." For those statistically significant declines in water quality, regressions with a 90% confidence value and a slope less than 0.0 are identified as having "SIGNIFICANT DECLINES." Confidence values of 75% to 90% are either "IMPROVING" or "DECLINING" with positive or negative slopes respectively. All other data is considered either "NO CHANGE" or "INSUFFICIENT DATA."

A further note on the selection of the reference time period window is worthy of discussion. Traditional integrated reporting has focused on a static time period or baseline of the year 2000 from which comparisons with each new report are made. As we continue to make progress in restoring water quality we expect the concentrations to change for the better. As such a moving reference period of the most recent data will prevent the IWQ trend from becoming asymptotic. Additionally older data may have been measured with a higher detection limit or censor which would produce less accurate reference values.

One of the great advantages of the seasonal nonparametric IWQ is that once the raw numeric water quality data have been scored against its own set of reference values, the scores can be combined from disparate sources. For example the U.S. EPA Chesapeake Bay Program Office maintains data from multiple state agencies and associations for the mainstem Bay and her tributaries. These data have been generated under standardized quality control procedures from sample collection to analysis. Sometime in the past it was determined that two laboratories involved in producing Bay program data were not using the same furnace temperature for the analytical method that determines Total Suspended Solids. As such there was a distinct bias between the two data sets although the samples were only separated by an imaginary geographic boundary, that being the border between Maryland and Virginia. Applying the IWQ to generate two sets of reference values one for each lab and then scoring the two sets of raw data against the matching quartiles produces data that can now can be combined into a single data set.

Another great potential for the use of the IWQ is combining benthic macro invertebrate scores across Ecoregions. There are differences in collection methods and scoring metrics among almost every group producing biological assessments. However all produce a score in the range of 0 to 100 which allows for the derivation of reference quartiles and further combination of scored data across the various techniques.

3. RESULTS

Data from the Department's twenty years (1991 to 2010) of statewide ambient water quality monitoring included results from 5,776 stations for bacteria, chlorophyll, Nitrogen, Phosphorus, suspended solids, pH, dissolved Oxygen, E.Coli, Enterococci, specific conductivity, and temperature. These represent 130,962 separate sampling collection events and 1,047,696 data points. The IWQ output from the analysis of these data generate 4,752 data set pages, one of which is displayed in Figure 1.

The IWQ categories for each parameter are summarized in Table 1. Notice that significant improvements are three times more prevalent that significant declines and improving is almost two times the declining category.

Although individual inspection of each of these IWQ line plots is important visualization using spatial watersheds accentuates the results. Figure 2 Integrated Water Quality Trends 1991 to 2010 Nitrogen in Rivers and Streams reveals the statewide results of water quality trends for Nitrogen in 314, 5th order watersheds.

	SIGNIFICANT DECLINES	DECLINING	NO CHANGE	IMPROVING	SIGNIFICANT IMPROVEMENTS	INSUFFICIENT DATA
BACTERIA	3	2	67	32	243	49
CHLOROPHYLL	18	23	186	48	50	71
NITROGEN	22	16	170	37	148	3
PHOSPHORUS	13	8	83	37	253	2
SUSPENDED SOLIDS	17	10	103	47	174	45
pH	97	30	152	36	80	1
DISSOLVED OXYGEN	68	42	191	28	66	1
E.COLI	38	27	213	28	52	38
ENTEROCOCCI	25	10	77	40	99	145
SPECIFIC CONDUCTIVITY	105	26	169	31	65	0
TEMPERATURE	26	23	253	35	59	0
TOTAL	432	217	1664	399	1289	355

Table 1 IWQ Counts by Scoring Category

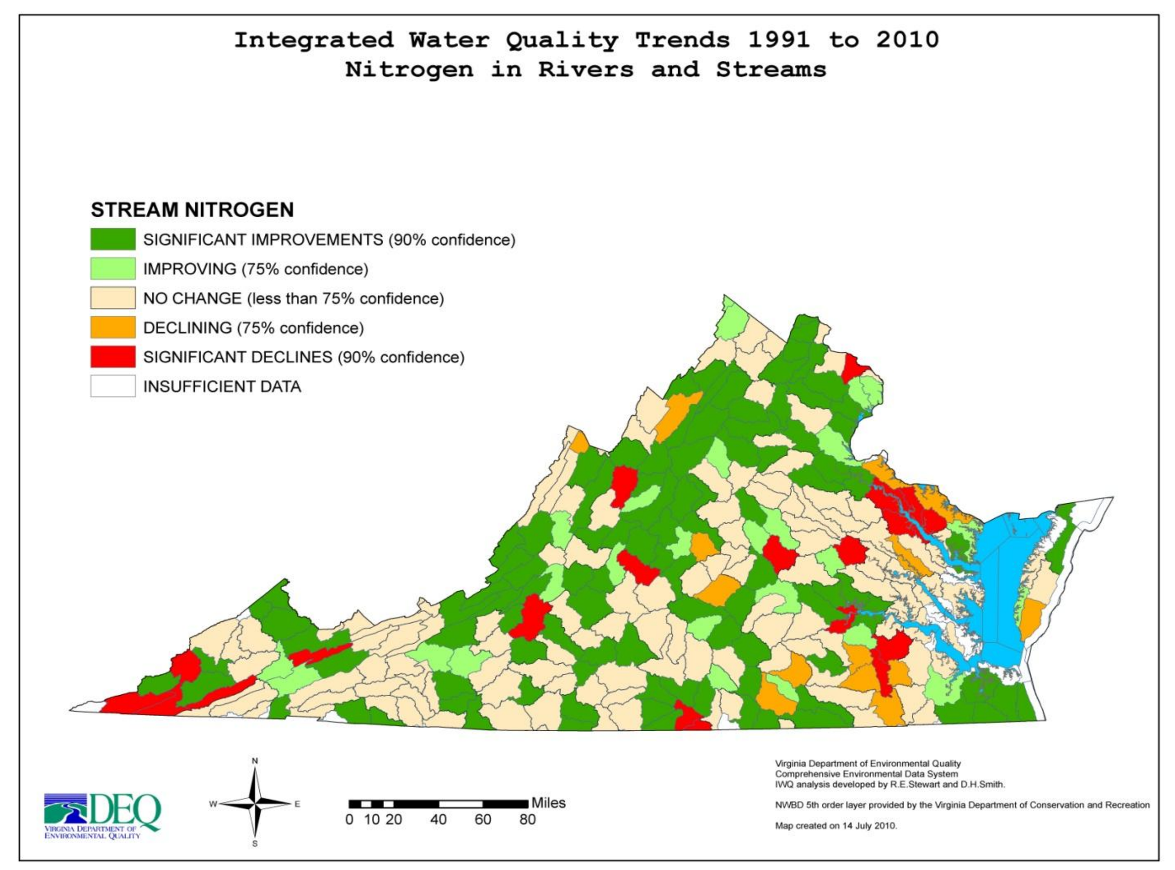

Figure 2 Statewide Total Nitrogen Trends in Rivers and Streams

4. DISCUSSION

We view the results of the IWQ analysis to have three beneficial uses. The first is to communicate to the public changes in water quality over time. The second is to track the success of Total Maximum Daily Load implementation projects aimed at restoration of impaired waters. The third is to provide a more targeted approach towards watersheds whose water quality that may be in decline.

SCENARIO 1 - A common encounter with the citizens of the Commonwealth goes something like this... Q. "What's the water like in the James River?" A. Well it's impaired for bacteria so at certain times it's not safe to swim. Q. "What's being done about it?" A. Because of our restoration efforts upstream we know that the James is getting cleaner. We can answer these fundamental questions using the results of our IWQ analysis and other formal trend analyses based on our fixed trend station network.

SCENARIO 2 - "Since 2002 more than $309,000 in section 319 funding has supported two full-time SVSWCD staff, who provide technical assistance to the Mennonite community and others in the project area. This support has generated nearly $839,000 in cost-share funds—approximately $200,000 of which came from farmers—to implement agricultural and residential BMPs. Finally, project partners used $130,000 in USDA/EQIP funds to install BMPs throughout the North River watershed." *Source: USEPA Non Point Source Program Success Story, Conservation Stewardship Puts Muddy Creek and Lower Dry River on Path to Recovery* http://www.epa.gov/owow/nps/Success319/state/pdf/va_muddy.pdf. This conclusion was based on the now outdated Virginia Water Quality Standards violation rates for Fecal Coliform bacteria at a concentration of 1000 CFU/ml, however simply counting the number of violation rates pre and post implementation does not accurately reflect the change in bacteria concentration over time. Scoring the actual numeric concentrations for bacteria over time using the IWQ approach we reveal the overall improvement in the watershed, see Figure 3.

SCENARIO 3 - The Occupacia Creek watershed in the Rappahannock basin has declining water quality conditions for three important indicators. The IWQ analysis reveals that Nitrogen, Phosphorus, and suspended solid concentrations are increasing, water quality is deteriorating. Future targeted monitoring within the watershed could help identify the source of these declines. Given limited resources for additional monitoring the IWQ can help identify those areas in need of additional data as well as those areas that don't, see Figure 4.

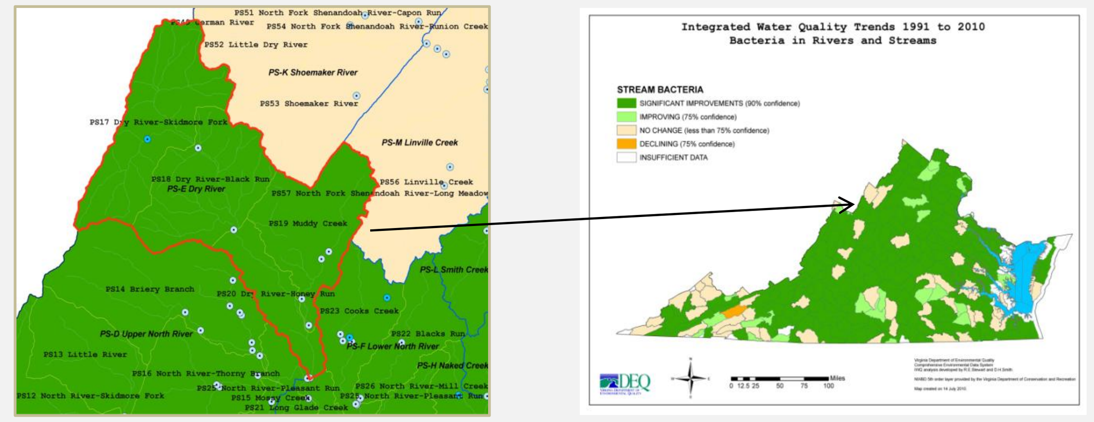

Figure 3 Statewide Fecal Coliform Trends in Rivers and Streams, Dry River and Muddy Creek Watersheds

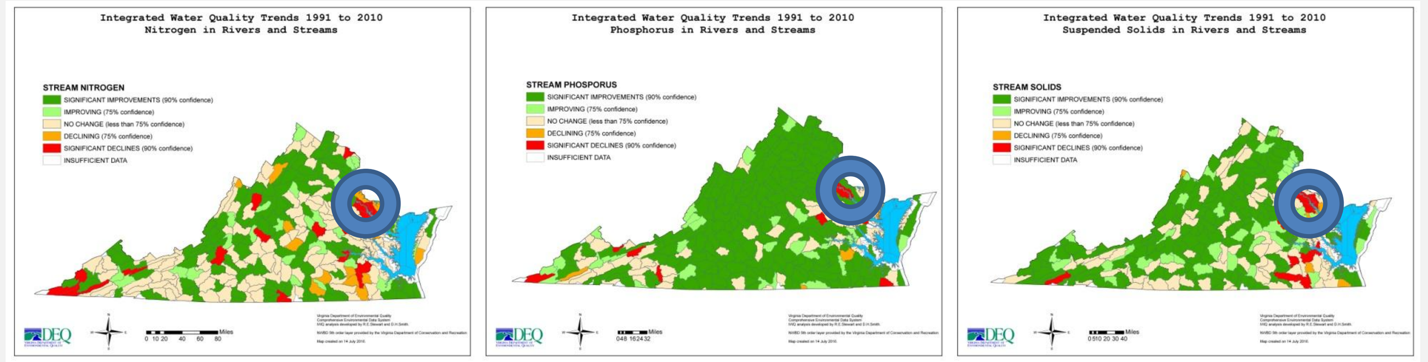

Figure 4 Declining Water Quality for Nitrogen, Phosphorus, and Suspended Solids in Occupacia Creek Watershed.

4. DISCUSSION, continued

Trend detection is an important tool for identifying our successes and where we need to apply our restoration efforts. As mentioned at the end of Section 2. Methodology, the flexibility of the IWQ to integrate data across jurisdictions, agencies, and even methods provides information on large geographic scales. As an example, Chesapeake Bay non-tidal benthic stream Index of Biological Integrity, IBI, scores for the entire Bay watershed provided to us by Jackie Johnson of the Chesapeake Bay Program where analyzed for trends using the IWQ analysis.

These scores are from a variety of State and Federal agencies using different methodologies to determine stream health based on benthic macro invertebrate metrics. In Virginia we have determined that there are at least two distinctive types of streams that require different biological indicators to accurately score stream health. The Virginia Stream Condition Index is applied to most streams west of the fall line and the Coastal Plain Macro Invertebrate Index is applied east of the fall line.

Regardless of the metrics used they all have the same endpoint of measuring water quality on a uniform numeric scale of zero to 100 which simplifies the IWQ analysis. Generally benthic samples are collected only two times a year, spring and fall, and are not seasonally different so average yearly scores are derived from all scores.

The IWQ methodology was applied to the Chesapeake Bay non tidal IBI data set which contains 13,551 individual scores from thousands of sites between the years 2000 and 2009. One of the first considerations in the use of the IWQ is what geographic scale or "by group" and are there enough data to calculate a meaningful trend. At the finest scale in the Bay watershed there are 2,196 6th order 12 digit sub-watersheds and 13,551 / 2,196 = 6.7 data points over a ten year period (6.7 / 10 = <1) which is not enough data to evaluate trends. Similarly at the 5th order 10 digit HUC watershed scale there are not sufficient data … 13,551 / 307 = 44 data points over a ten year period, 44 / 10 = 4.4 data points per year. A suitable density of stations is obtained at the eight digit hydrologic unit code resulting in an average 26 data points per year.

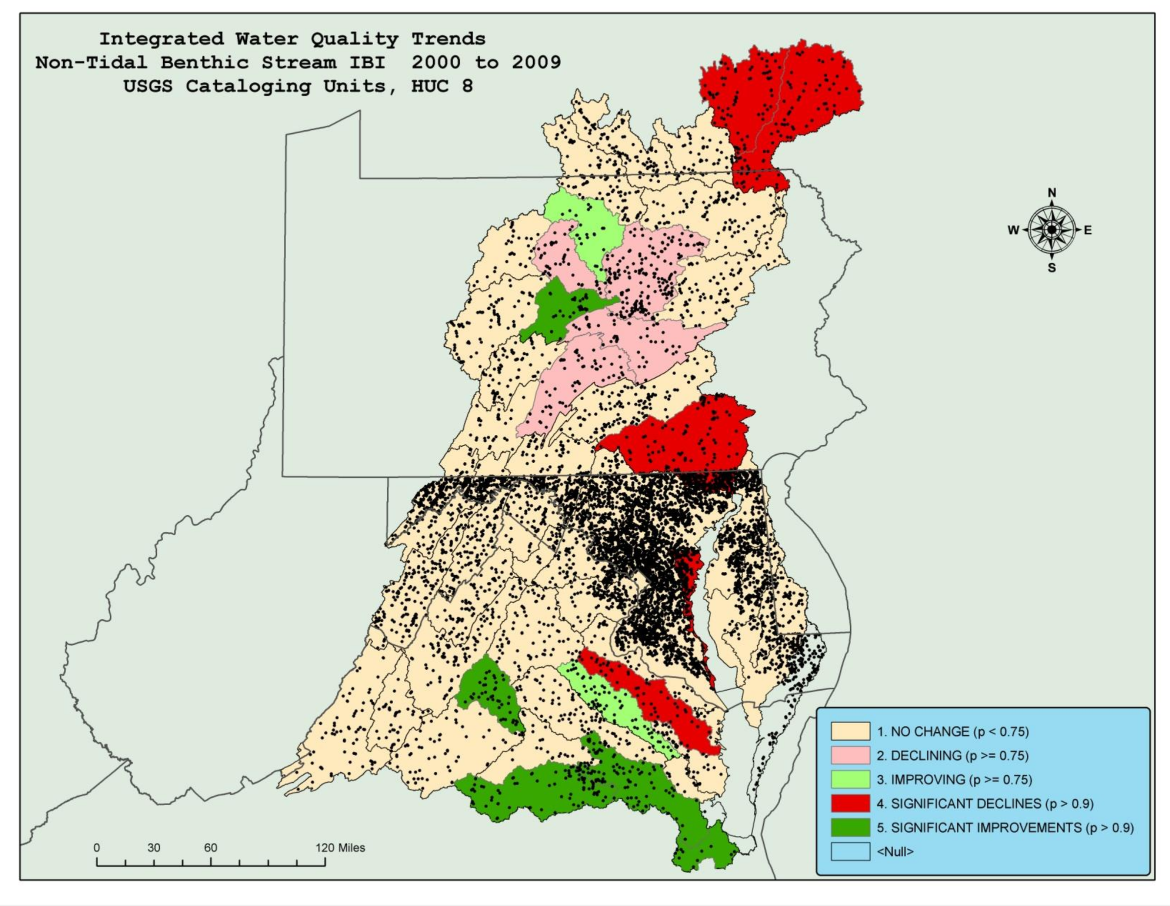

Figure 5 Chesapeake Bay Non Tidal Integrated Benthic Macro Invertebrate Water Quality Trends as Derived by the IWQ Methodology

5. CONCLUSIONS

As monitoring programs mature data analysis and interpretation are becoming essential to our understanding of the environment and the processes that influence our ecosystem. We must improve our statistical tool box so that we can better communicate our successes and challenges. Simply counting the numbers of impaired waters or how many TMDLs were implemented or how many waters were delisted does not provide the level of detail needed to make informed decisions on our progress.

When the results from the IWQ trends are compared to those of modified seasonal Kendall analysis from a fixed trend station in the same watershed, the results are generally in agreement. A typical display from our fixed trend station network can be seen in Figure 6. While the Kendall[1,3] trend represents changes at a single site, the IWQ integrates data at numerous sites within the watershed into an annual distribution and comparisons of the changing distributions from year to year reveal the direction and relative intensity of trends.

Assigning a direction (improving, declining, or no change) and a significance level (highly significant, moderate, or insignificant) to each watershed and mapping their statewide distribution reveals regional tendencies in incrementally changing water quality for each variable. For some variables (e.g., bacteria, phosphorus) statewide improvements in water quality predominate and localized declining tendencies in water quality are easily identified. These improvements are independently of numbers of impairments and delistings as reported in our 2012 Integrated Report[4]. For other variables (e.g., nitrogen and suspended solids) regional distributions are less uniform, indicating less success in controlling those variables.

The next step in developing the tool is to overlay the regression of annual mean concentration in order to facilitate visual comparisons with water quality standards or other threshold values and quantify the relative rates of change being observed.

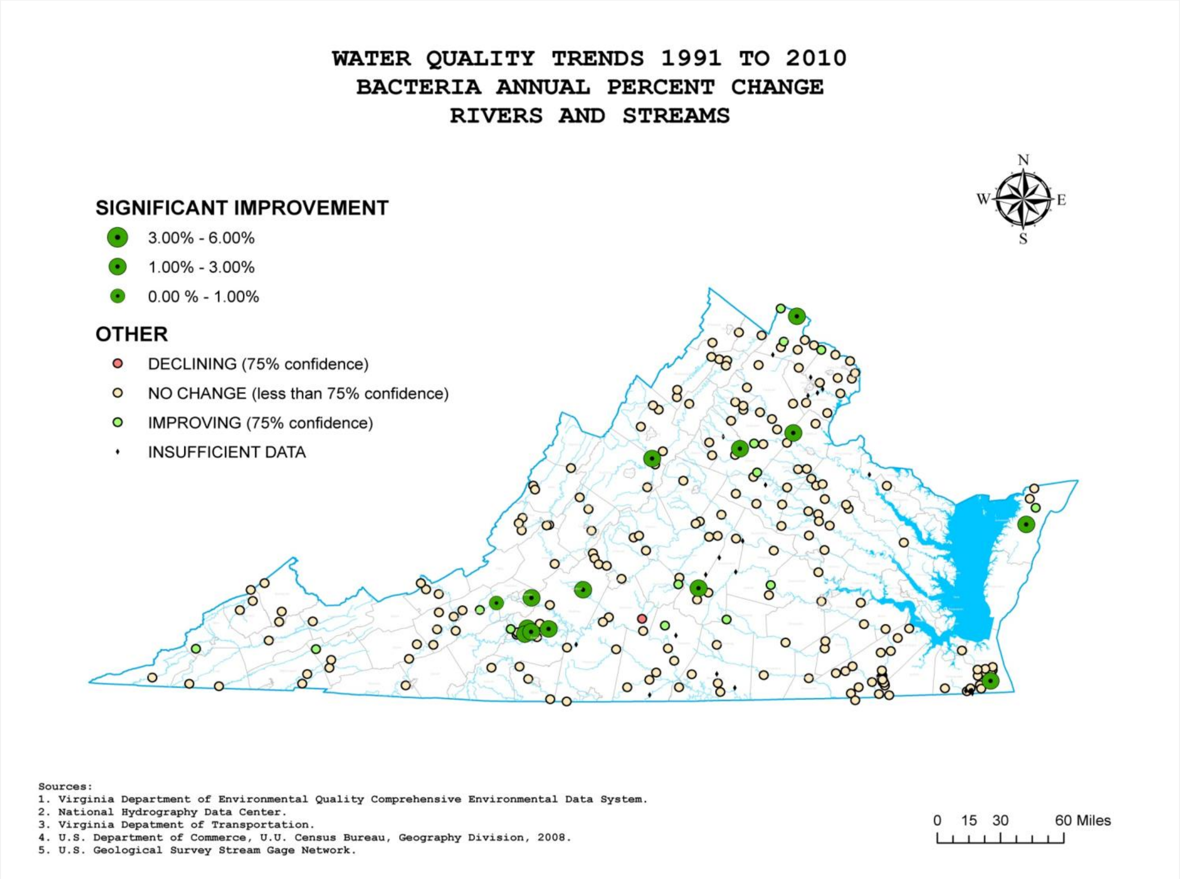

Figure 6 Fecal Coliform at River and Stream Stations, Modified Seasonal Kendall Trends, non Flow Adjusted

REFERENCES

1. Kendall, M. (1970). *Rank Correlation Methods, Griffin, London.*
2. Gilbert, R.O. (1987), *Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold Company, New York.*
3. Hirsch. R.M., Slack, James R., and Smith, R.A. (1982), *Techniques of trend analysis for monthly water-quality data, Water Resources Research, 18(1), pp. 107-121.*
4. *2012 Integrated Report, Virginia Department of Environmental Quality, April 2012.*